A review of anthropogenic stressors on Lake Sevan, Armenia

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ABSTRACT

The resilience of natural systems may be severely compromised by anthropogenic influences. In this paper, the principal anthropogenic influences on the ecosystem of the Armenian highland lake Sevan during the past century are identified. The diversity and severity of the pressures were influenced by national priorities and the catchment's growth. Changes in the lake's morphometry and the littoral's morphology, as well as unsustainable usage of the lake's fish resources, were among the repercussions. They are discussed depending on how each sort of disturbance affects the ecosystem. Although the timing and degree of each stressor were specified, identifying the direct effects of each stressor was often challenging. The current management decisions and future threats to the lake's ecosystem are discussed. This article describes the history of the anthropogenic change of Lake Sevan and, using it as an example, assesses the ecological footprint of people on natural resources and their repercussions.

INTRODUCTION

Human activity has had a significant impact on aquatic ecosystems around the world. Lake Sevan in Armenia is a prominent example of ecosystem degradation caused by human activities. It is also one of the most overfished and degraded freshwater ecosystems in the world, suffering from nutrient input, biodiversity loss, overfishing, water abstraction, and habitat degradation. Long-term anthropogenic pressures have converted an oligotrophic "trout" lake into a mesotrophic to eutrophic "carp" lake (Hovhanissian and Gabrielyan, 2000). In roughly 50 years, water abstraction has decreased the lake's water level by nearly 19 meters, leading to the depletion of spawning grounds for endemic fish species and the extinction of the commercial trout stock (*Salmo ischchan*). Lake whitefish (*Coregonus lavaretus*), which was successfully introduced between 1924 and 1927 and reached commercial significance in the mid-1960s, has been decimated by unrestricted and excessive fishing since the beginning of the 1990s (Gabrielyan, 2010). In addition to the lowering of the water level, land use practices in the catchment have facilitated the introduction of pollutants and nutrients, elevating the lake's trophic state and promoting the occurrence of cyanobacterial blooms (Hovhanissian, 1994). Accidental introductions of various fish species and crayfish led to the establishment of stable populations.

In this review, significant drivers of change of the ecosystem of Lake Sevan are discussed in order to determine the major effects of anthropogenic stressors on this vulnerable mountain lake's ecosystem. The most important anthropogenic changes were i) the fluctuations in water level and water budget, ii) increasing numbers of inhabitants and land utilization within the drainage basin accompanied by eutroph ication and iii) the changes in the fish population. Since the majority of these drivers acted concurrently, it is difficult, and sometimes impossible, to identify their individual effects. Nonetheless, we aim to provide a comprehensive summary and consistent description of the most significant changes, in terms of both magnitude and timing. Another objective of this study is to evaluate past

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management decisions and to identify potential future risks and management guidelines for the lake.

Lake Sevan

Lake Sevan is a mountain large lake situated approximately 1900 m above sea level. It constitutes the largest surface freshwater resource in the Caucasus region (Fig. 1). The north-eastern shore of the lake is an ophiolitic structure while the western and southern banks are formed by linear volcanic ridges (Karakhanian *et al*., 2001; Wilkinson 2020).

Lake Sevan consists of two parts that are separated by the Artanish and Noraduz peninsulas at one point only 7 km wide (Wilkinson, 2020). According to their size, the two parts are named Small Sevan (SS) and Big Sevan (BS). BS is shallow and large with a relatively smooth shoreline. SS is characterized by a greater depth, lower volume, a smaller surface area and a rugged shoreline (Hovhanissian, 1994). Following the definition of Herdendorf (1982), the whole Lake Sevan and even BS alone are large lakes having a mean surface area of >500 km^2 (Tab. 1).

Major anthropogenic impacts and their consequences

Changes in water level and water balance

In 1931, the government of the Republic of Armenia developed a plan to utilize the lake's water for irrigation and power generation. According to the plan, the water level should have been reduced by 50 meters over the course of fifty years. A channel and two short tunnels were built to increase the outflow from Lake Sevan via its sole outflow, River Hrazdan (Hovhanissian, 1994; Meybeck *et al*., 1998).

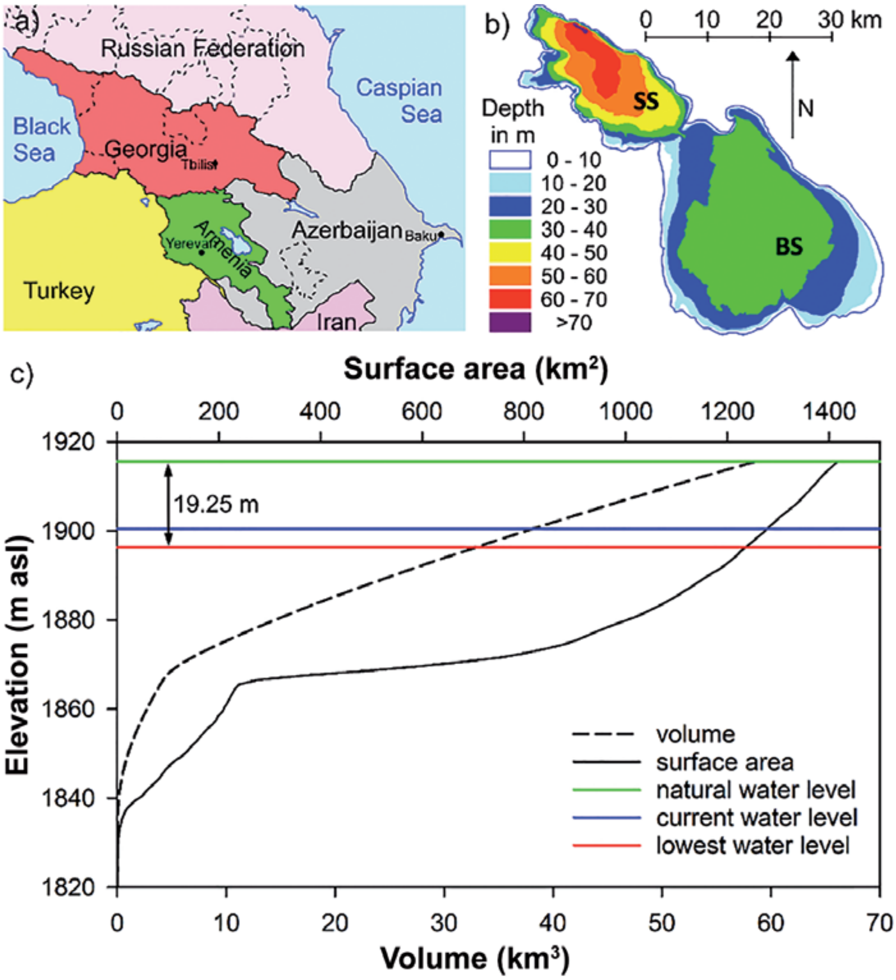

Fig. 1. a) Location of the Lake Sevan in Armenia. b) The northwest part of the lake is called Small Sevan (SS) while the southeast part is called Big Sevan (BS). c) Lake volume and surface area as a function of the altitude; horizontal lines: initial (green, 1915.54 m asl), current (blue, 1900.43 m asl and maximum lowering of the water level since the 1930s (red, 1896.32 m asl.). Based on data provided by the Hydrometeorology and Monitoring Center SNCO of the Ministry of Environment RA.

After the lowering, it was planned to cultivate the dried up areas of the lake. The peak of water abstraction occurred between the late 1940s and early 1950s. It continued at slower rate until the 1980s, resulting in a water level drop of around 19 m (Fig. 2). The consequences of the water abstraction for the ecosystem functioning in Lake Sevan were not considered at the planning phase but since the end of the 1950s, it has become clear that the ecological status of Lake Sevan has been negatively impacted by the water withdrawal. Both, the littoral macrophyte zone and spawning/nursing sites of endemic fish species were destroyed. Trout stock was dramatically reduced, and for the first time harmful algal blooms were observed. As a consequence, fishery was also disrupted reflecting the substantial environmental and economic costs of water withdrawals. Moreover, the exposed soils in the former littoral were unsuitable for agriculture (mainly sandy, humus-free, highly erosive). In addition, the amount of abstracted water available for hydropower was insufficient to produce enough electric energy to satisfy the demand.

In 1961, the government decided to divert water from neighboring catchments to the lake for more efficient power generation and in 1962 it was decided not to lower the water level by more than 18 m (Hovhanissian, 1994; Meybeck *et al*., 1998). Additional tunnels were built to supply the lake with water from neighboring river systems (Arpa River; tunnel 48.3 km in length and inaugurated in 1988) and Vorotan River (tunnel 21.6 km in length and inaugurated in 2003).

In the 1980s, some stabilization and even an increase of the lake's water level were finally achieved (Fig. 2), as a result of a reduction of water abstraction, installation of additional power generation plants, and diversion of additional river water into the lake.

Nonetheless, a second period of water abstraction occurred in the 1990s during the post-Soviet, severe economic crisis when the lake was intensively used for power generation albeit on a smaller case than in the 1950/60s.

Since 2003, the government decided to increase the lake's water level by 6 m as part of the restoration program. Due to reduced withdrawal and several consecutive years of adequate precipitation, the water level rose 3.81 m between 2001 and 2011 (Fig. 2). Rising of the water level has caused the inundation of nearby land that was cultivated over the past 20 years. Although not continuously quantified, the water level rise has resulted in the input of both organic matter and nutrients from decaying vegetation (Davtyan, 2010). Compared to previous years, the water level since 2013 has remained relatively stable fluctuating by only 5-30 cm per year. Fig.

Tab. 1. Morphometric characteristics of Lake Sevan prior to the artificial lowering of the water level (1930), at the intermediate minima and maxima after lowering (1981, 1990, 2001) and at present (2020).

	1930	1981	1990	2001	2020
Water level, m asl	1915.54	1897.09	1898.00	1896.32	1900.43
Volume, km^3	58.5	33.9	35.0	32.9	38.1
Area, km^2	1416.0	1244.4	1253.5	1236.2	1277.8
Max depth, m	97.9	79.5	80.4	78.7	82.8
Mean depth, m	41.3	27.2	27.9	26.6	29.8

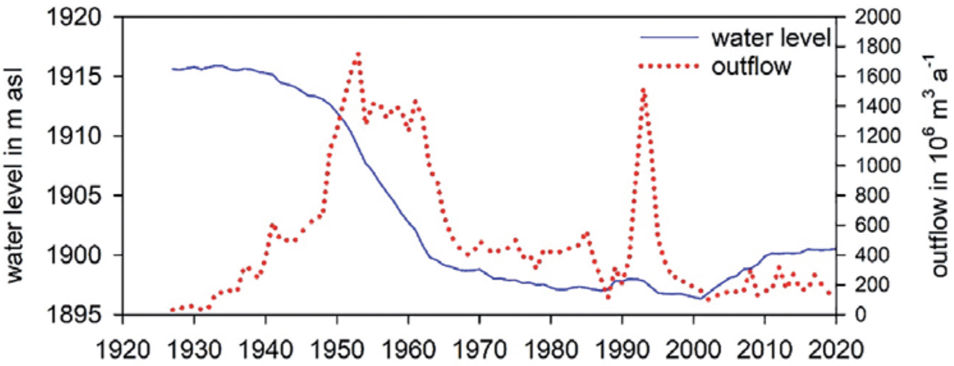

Fig. 2. Dynamics of the artificial lowering of the level of Lake Sevan by year (data provided by Hydrometeorology and Monitoring Center SNCO of the Ministry of Environment of the Republic of Armenia (HMC))

2 and Tab.1 depict water level, depth, volume and surface area of the lake since 1927 both before and after withdrawal.

The lowering of the water level has altered the thermal regime of both parts of the lake but differently. While SS due to its larger depth did not change much, the shallower BS was significantly impacted. During some years (May-June) the thermocline reached down to the bottom of the lake. No hypolimnion did exist (Poddubny, 2010). Before the start of water level management, the bottom temperatures in BS ranged around 4.2-5.0°C. In the 1990s, it had risen to 8-12 °C (Hovhanissian, 1994). In addition, thermal stratification started in May (3.5-4.0 °C) and lasted until August (18-19 °C) before the artificial lowering of the water level. From 1982-1988, it already began by the end of April (4.0-4.5 °C) and maximum temperatures were detected at the end of July (19-20 °C) (Hovhanissian, 1994).

Like water temperature, the thermal stratification pattern has changed as well. While autumn mixing in SS from 1952-1955 started at 5.5-6.2 °C, it began at 6.5-7.0 °C during 1961-1965. In BS during 1952-1955 it was observed at 7.0-8.4 °C but had changed to 10.5-12.5 °C from 1961-1965 (Gezalyan, 1979). Prior to the water level decline, the lake was completely ice-covered only once in 15-20 years. Subsequently, it froze up nearly every year (Gezalyan, 1979). Currently, complete ice cover occurs roughly every seven years (Ministry of Emergency Situations RA, http://mes.am/en/news/item/2017/02/15/65465465/). However, no significant changes have been observed in the hydrodynamic regime of the lake following the water level rise of 3.1 m in 2019 compared to the 18.63-meter drop in 1981. During summer and autumn, a dome of cold water forms in both regions, causing cyclonic water circulation. In the autumn, due to deepening of the thermocline to the bottom, the hypolimnion of the dome is isolated from the nearby well-mixed water layers and becomes a big reservoir of hypoxia (oxygen content <2 mg L^{-1}). Electrical conductivity throughout the water column of the lake is homogeneous. Short-period internal waves play important role in the distribution of nutrients in the water column (Poddubny, 2010).

Changes in land use intensity and eutrophication

Parallel to the changes in water level and in water balance, the number of inhabitants dwelling the catchment area of the lake increased and the land use was considerably intensified. According to Hovhanissian (1994) the population grew from 158,000 inhabitants in 1940 to 256,000 inhabitants in 1990. Presently the population amounts to 212,000 (EUWI+ 2021). Wastewater treatment

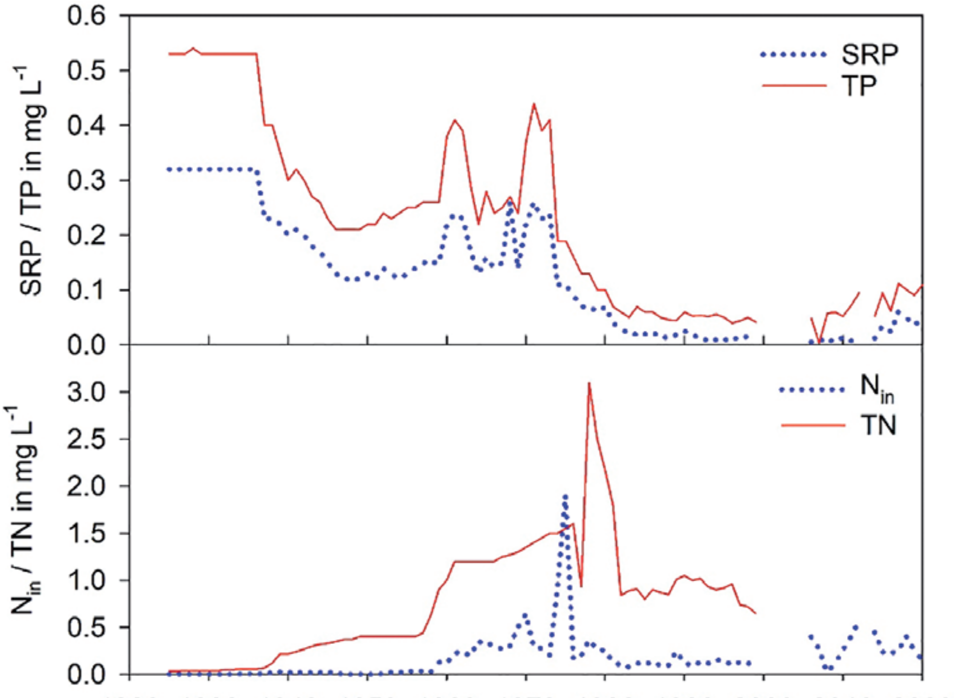

Fig. 3. Concentrations of nitrogen and phosphorus in Lake Sevan (sources: data of the Scientific Center of Zoology and Hydroecology and Hovhanissian, 1994). N_{in}, inorganic nitrogen; TN, total nitrogen; SRP, soluble reactive phosphorus; TP, total phosphorus.

plants were implemented during the 1960s and 1970s. However, they did not have efficient nitrogen and phosphorus removal technique. Furthermore, due to missing maintenance they became less effective over time (EUWI+ 2021). Also, fertilizers were increasingly used in agriculture. The amount of nitrogen added to the catchment as fertilizer rose from 2,280 t a^{-1} in 1960 to 13,223 t a^{-1} in 1984 but then declined to 1,937 t a^{-1} in 1990 (Hovhanissian, 1994). For phosphorus, Hovhanissian (1994) reported an increase from 1,123 t a^{-1} in 1960 to 6,450 t a^{-1} in 1984 followed by a decline to 1,775 t a^{-1} in 1990. Current detailed data are not available (EUWI+ 2021). However, the overall amount of used mineral fertilizers (nitrogen, phosphorus, potassium etc.) reported by EUWI+ (2021: 21,000 t a^{-1}) suggests that the current quantity is similar to that of 1990. All these impacts contributed to the observed changes of nitrogen and phosphorus concentration of Lake Sevan as shown in Fig. 3.

The data until the 1980s provided in Fig. 3 are largely historical. The methods used for the chemical analyses were not always the same as the modern standard methods. Furthermore, the filters and chemicals used for the analyses probably were not always adequate. Such problems were reported by Ohle (1938) regarding the quality of sulphuric acid used for phosphorus analyses. For analyses of SRP and Nin, it is still important to select filters that do not release phosphorus or nitrogen during filtration. This must be taken into account when interpreting the data presented. Such factors were unquestionably responsible for the historically reported concentrations' abrupt peaks and drops.

In order to evaluate the reliability of these P- and N-peaks and drops, the nitrogen and phosphorus content of the lake was calculated by multiplying the concentrations with the volume and then related to the quantity of fertilizers applied in the catchment. For example, the peak in dissolved inorganic nitrogen from 1974-75 required an input of about 55,000 t of nitrogen while the amount of nitrogen added to the catchment was only about 4,400 t a^{-1} in those years (Hovhanissian, 1994). The maximum TP concentration during the years around 1960 is equivalent to an addition of about 3,000 t of phosphorus. This is almost three times the annual amount of fertilizer applied at that time (Hovhanissian, 1994). Alternatively, almost 1.7 million persons were needed to obtain 3,000 t of phosphorus when assuming a daily equivalent of 4.9 g phosphorus per person into waste water (Bernhardt *et al.*, 1978). Therefore, these rough estimates indicate that the sharp changes in the long-term dynamics of P- and N-concentrations shown in Fig 3 may not be reliable. However, these historical data indicate the dynamics of the changes in the nutrient content in the lake resulted from the socio-economic transformation of the catchment. In particular, one can see a steady decrease of the phosphorus concentration alongside with a similar increase of the nitrogen concentration until the 1960s (Fig. 3).

High nutrient concentrations accelerated phytoplankton growth resulting in an increase of algal biomass from 0.2-0.5 g m^{-3} (1937-1962) to 2.0-3.0 g m^{-3} (1976-1983) and led to changes in the phytoplankton community structure. Before lowering the water level, the phytoplankton community in the lake was similar to that of other mountain oligotrophic lakes (Hovhanissian, 1994). Diatoms dominated in the community reaching the maximum biomass in the winter-spring period. In the summer period, the phytoplankton community's diversity was 27 species versus to 8-12 species in the winter period (Vladimirov, 1939). Previous researchers stressed regular fluctuations in the numbers of some species and the existence of their sustained succession in different years. The maximum phytoplankton biomass was at 20-30 m depth (Hovhanissian, 1994). With water level lowering, cyanobacteria and green algae became constant components of the community while the formerly diatom-dominated assemblage decreased. From 1976-1984 the planktonic primary production in the lake increased 3-7-fold compared to 1969 (Hovhanissian, 1994). The first blooms of cyanobacteria (*Anabaena flos-aquae* and *Aphanizomenon flos-aquae*) were recorded in 1964 (Legovich, 1968). An increase in the phytoplankton biomass is one of the indicators of the lake's eutrophication (Hovhanissian, 1994).

The long-term dynamics of the average annual zooplankton, zoobenthos and phytoplankton biomass demonstrate an increasing trend during highly productive period of the lake from 1977-1979 followed by a decline at the beginning of the 1980s when the water level was somewhat stabilized (Figs. 2 and 4).

Zooplankton biomass went down dramatically during the massive growth of whitefish stocks while phytoplankton is increasing (Figs. 4 and 5 Krylov *et al.*, 2013, 2015, 2016b, 2018, 2019, 2021). This corresponds to the classical trophic cascade in lake food webs (Carpenter *et al.*, 1985). Large zooplanktivorous fish stocks feed on zooplankton and decrease their biomass to such a low level that grazing losses of phytoplankton are minimized. In Lake Sevan, this cascade effect is visible in the 80s and is afterwards reverted when whitefish stocks decreased to low stocks (Figs. 4 and 5). Whitefish is the main pelagic consumer of zooplankton in the lake. During times of low whitefish stocks, zooplankton reached high biomass, phytoplankton remained lower and vice versa. Another remarkable observation is the occurrence of large-bodied *Daphnia magna* during the low planktivory in the past decade. In October 2013 and 2014 sampling in BS showed that *D. magna* dominated by biomass and numbers at the depths 7 and 15 m: 20-30 g m^{-3} and 180-200 thousand ind. m^{-3} (2013) and 13-40 g m^{-3} and 60-160 thousand ind. m^{-3} (2014), respectively (Krylov *et al*., 2016a). This proliferation of large-bodied zooplankton is considered only possible if the abundance of visually feeding zooplanktivorous fish is low (Brooks and Dodson, 1965, Hülsmann *et al*., 2005). This may point to the importance of top-down processes in the lake as related to whitefish biomass dynamics. Average values of phytoplankton biomass in Lake Sevan decreased from 2005-2009 and approached values typical for mesotrophic lakes. In some periods, however, cyanobacteria blooms were recorded (e.g., in October 2009, July 2018-2020) indicating that the nutrient supply in the lake can still support eutrophic conditions (Gevorgyan *et al*., 2020; Hambaryan *et al*., 2020; Sakharova *et al*., 2020).

The macrophyte community also experienced substantial changes. The water level draw down caused a downward shift of the littoral zone. Before lowering, due to high water transparency (14 m in average) the macrophytes (mainly *Chara* sp.) reached significant depths (occupying the area of depth 6-19 m in the littoral) and served as important habitat structure for phytophile benthic organisms such as gammarids, an important diet component for Sevan fish (Hovhanissian, 1994; Hovhanissian and Gabrielyan 2000; Markosyan, 1951). The major loss of macrophyte area in the littoral occurred during the 1950s as a result of swift water level lowering (Fig. 4, Hovhanissian, 1994). In the mid-1970s the diversity and biomass of the macrophytes was drastically

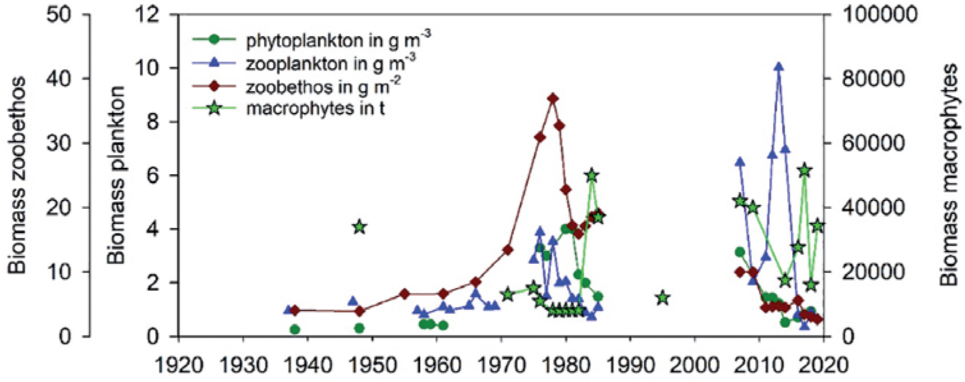

Fig. 4. Dynamics of average annual total biomass of zooplankton, phytoplankton, zoobenthos and macrophyte in Lake Sevan from 1938-2019. Zooplankton biomass in 2019: spring and summer periods only. Macrophyte biomass represents the minimum measured biomass as includes data either by select species or by select part of lake. Missing data: unavailable. Source: zooplankton (Meshkova, 1975; Krylov *et al*., 2010; Krylov *et al*., 2016a, 2016b; Simonyan, 1991); phytoplankton, zoobenthos, zooplankton (data of the Scientific Center of Zoology and Hydroecology).

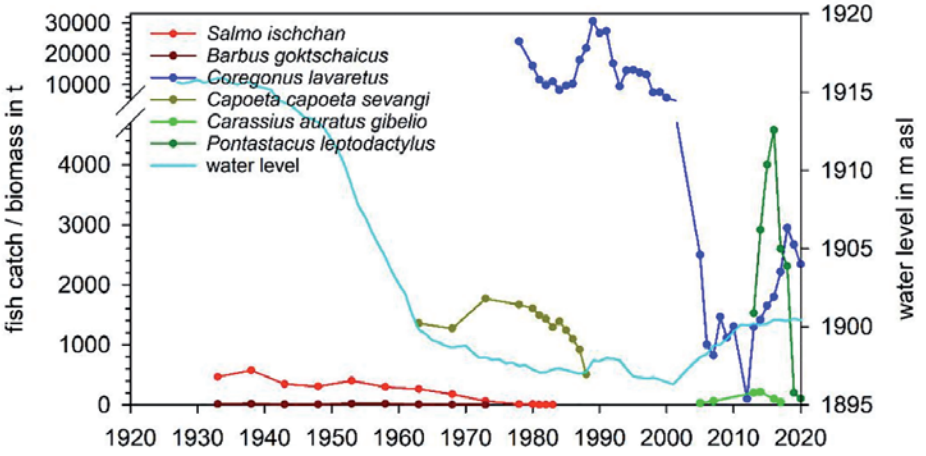

Fig. 5. Dynamics of catch, stock biomass and water level change in Lake Sevan during 1933-2019. Catch: former commercial stock *S. ischchan* and *B.goktschaicus.* Total biomass: *C. capoeta sevangi*, *C. lavaretus, C. auratus gibelio*; fishery biomass of *P. leptodactylus*. Data derived from Gabrielyan *et al*., 2022.

reduced. In particular, *Potamogeton natans*, *P. pusillus, P. densus* and other species could only be found occasionally while *Chara* sp. were met as single examples (Hambaryan, 1979). Since the middle of the 1980s the macrophyte biomass rose again because the water level was stabilized or even increased (Fig. 4). Further, due to water level rise since 2014 a new macrophyte community developed occupying the depth from 0-10 m which in some places might reach 15 m. The most spread species were *Chara fragilis*, *P. perfoliatus* L., *P. pectinatus* L., *Myriophyllum spicatum* L., *Ceratophyllum demersum* L. With except of *C. fragilis*, all other species are characteristic for mesotrophic lakes. While *C. fragilis* was the most frequently-met species, by biomass *P. perfoliatus* L. dominated (Scientific Center of Zoology and Hydroecology, Republic of Armenia, Annual Report, 2018; unpublished). In the last 20 years, the biomass of macrophytes varied within a range similar to that reported from the 1940s. The appearance of the new macrophyte community was stipulated by the physico-chemical changes in the lake's ecosystem such as temperature, chemical content, oxygen, nutrients, substrate.

Changes in the fish population and its management

The original fish community of Lake Sevan was distinctive due to the presence of three fish species that had adapted locally to this geographically isolated habitat. The endemic Sevan trout *Salmo ischchan* Kessler, 1877 included four ecological races: Winter trout (*S. i. ischchan* Kessler, 1877), Gegarkuni (*S. i. gegarkuni*, Kessler, 1877), Summer trout (*S. i. aestivalis* Fortunatov, 1926), and Bodjak (*S. i. danilewskii*, Iakowlev, 1888). The races differed by a number of biological and morphological characteristics. The Winter trout reproduce in the lake during the late autumn-winter period. The Gegarkuni spawn in rivers at the same period. The Summer trout spawn in rivers in spring, and the Bodjak spawn in the lake during winter and early spring. Two cyprinid fish species dwelling the lake were the detriitophages Khramulia (*Capoeta capoeta sevangi*, Filippi 1865) and the benthivores Barbell (*Barbus goktschaicus,* Kessler 1877), Anthropogenic intervention into the lake's fish community started in the 1920s when the introduction of a new fish species was decided. This action rested on the assumption that the pelagic consumer niche was empty because no planktivorous fish species lived in the lake. Thus, two whitefish species *Coregonus lavaretus ludoga,* Paljakow 1874 and *C. lavaretus maraenoides,* Poljakow 1874 were acclimatized from 1924-1927 giving rise to a new local hybrid form *C. lavaretus natio sevangi* (Mailyan, 1967).

Dropping the water level and the loss of former littoral zone significantly impaired the native fish community (Fig. 6). The major spawning grounds were lost, feeding and habitat conditions of juvenile fish deteriorated. This

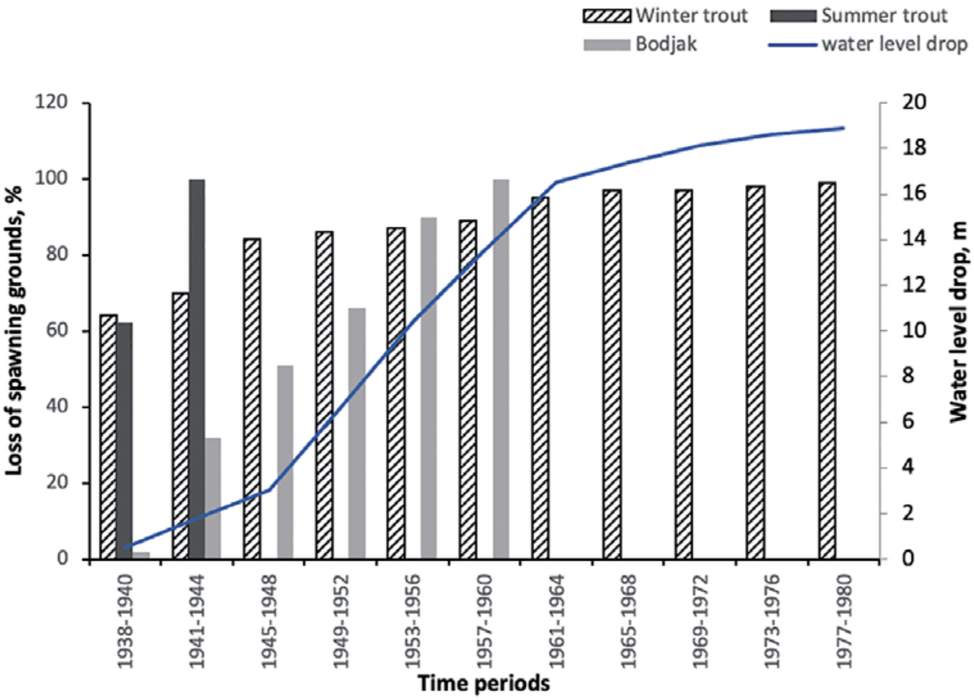

Fig. 6. Lake Sevan water level drop and the percentage of lost spawning grounds of the endemic trout sub-species (Winter trout, Summer trout, Bodjak) from 1938-1980 (Smoley *et al.*, 1985).

is especially true for the 1940s when major losses of spawning grounds occurred (10-15 years after the beginning of water withdrawal) (Gabrielyan, 2010). Collectively, these changes resulted in a dramatic decrease of the endemic commercial fish stock (Fig. 6).

Fig. 5 shows dramatic declines in the catch of the main commercial fish species Sevan trout *S. ischchan*. Declines in the catch directly reflect the diminished numbers of their populations following the destruction of spawning/feeding grounds and habitats of this endemic species (Fig. 6). Khramulia *C. capoeta sevangi* stock existed until the 90s but then drastically reduced due to a loss of spawning grounds in the lake and overfishing during the spawning period in the rivers (this species spawn in both the lake and the rivers). It shall be noted that in the past, fishery was realized by a state organization. Stock dynamics was estimated based on data regularly provided by that organization. However, due to the transition from the state-controlled fishery to the privately-owned fishing companies since the 1990s, no data on fish catches are available. Yet, an application of a virtual-population analysis method (VPA) since the 1990s for Khramulia and whitefish in combination with echo-sounding permitted the estimation of total and fishery biomass. In particular, in Fig. 5, the total biomass of *C. capoeta sevangi* was retrospectively estimated by a VPA method.

The population of whitefish (*C. lavaretus*) reached stable growth by the 1980s with a total biomass of nearly 30,000 t in 1988) (Gabrielyan, 2010). It was the only commercially important species at that time. However, it has been overfished afterwards. The beginning of the 2000s was accompanied by uncontrolled fishing that resulted in massive overfishing. Stock estimates point to a reduction by one order of biomass from approximately 30,000 t down to below 5,000 t. Since 2006, fishing has been prohibited because of the small size of the remaining stocks. However, poaching started and exerted an unprecedented pressure on the *C. lavaretus* stock leading to its strong suppression to a total biomass nearly 2,000 t in 2019 (Fig. 5).

Recently, a governmental program for the restoration of the Sevan trout stock *S. ischchan* through a cage-based aquaculture in the lake has been installed. This program should serve both, the production of commercially available fish as well as the production of hatchlings to be released into the lake in order to restore the salmonid stocks. It can be an important step toward re-stocking of the lake with a valuable trout species taking into account the dramatic state of the fish community. However, aquaculture is also raising concerns with respect to the increased input of phosphorus and nitrogen (Azevedo *et al*., 2011; Canadian Science Advisory Secretariat, 2015). Therefore, a quantitative analysis of nutrient fluxes that are associated with the aquaculture is required as well as an assessment of the survival and efficiency of the restocking efforts.

In August 2016, a pilot fish culturing facility for breeding two river-spawning races of Sevan trout (Summer trout and Gegarkuni) was put into operation in BS. The aquaculture facility with six cages had operated until December 2016 but was stopped afterwards. Since July 2017 nine cages have been installed in SS and still operate. The cages are regularly supplemented with fry/fingerlings from the fish hatchery. Currently, 12 cages are installed producing on average 120 t of fish per year, in average (data from ‘’Sevani Ishkhan CJSC’’).

Prussian carp *Carassius auratus gibelio* (Bloch, 1782), an accidentally introduced fish species, was first seen in catches from 1981-1983. By the end of the 1980s its annual catch amounted to 8 t. By 2005 it exceeded 200 t, making the fish the second most important commercial species in terms of catch and biomass followed by whitefish (Gabrielyan, 2010). Afterwards, however, the carp stocks gradually declined due to overfishing and fish diseases. From 2013-2016 the carp catch amounted to 10-20% of the whitefish catch. Afterwards it had decreased to as little as 2%.

Finally, *Pontastacus leptodactylus* Eschscholtz, 1823 was accidentally introduced into the lake in the 1980s. The commercial stock of the crayfish increased from 1,528 t in 2013 to 4,580 in 2016, but afterwards primarily due to overfishing has decreased to 105 t in 2020 (Scientific Center of Zoology and Hydroecology, Republic of Armenia, Annual Report, 2014, 2020; unpublished).

Climate change

According to the projections of the World Bank Group (2021), the predicted average temperature increase in Armenia under the highest emission pathway will be about 2 °C by 2050 and 5 °C by 2090. By the end of the century, the number of summer days is likely to increase drastically, while the number of freezing days is expected to fall. Furthermore, despite the existing data exhibit no statistically significant trend, annual precipitation is expected to decrease by 27 mm in 2040-2059. Almost all rivers in Armenia are fed by a combination of snowmelt (from 20-40%), precipitation (around 10%) and groundwater (up to 40%). According to USAID (2017), rising temperatures will increase evapotranspiration losses, resulting in a decrease in discharge. Moreover, the current patterns of snowfall and snowmelt are likely to change. Snowmelt may begin earlier and a portion of today's snowfall may turn into rain by the end of this century. Thus, all 28 rivers draining into Lake Sevan will likely contribute less runoff. Declines in precipitation and increasing evapotranspiration will eventually impair groundwater replenishment and storage which in turn will further aggravate the freshwater supply from these sources due to decreasing river baseflow. The shrinking supply is likely to be confronted with likely increasing demands for irrigation and drinking water. While agricultural usage has been at large scale, until now, the lake is not used for drinking water purposes. If drinking water shall be provided, a comprehensive assessment of future water availability is required in order to dimension future water abstractions to a sustainable level. Otherwise, a new period of water level decrease will be initialized due to the overuse of water from the lake. This also points to the fact that less water will be available for hydropower generation and the energy production will be affected as well.

Until now, according to the 5th National Report of Armenia to the Convention on Biological Diversity of 2014, climate change effects were not appreciated as visible in the country (Republic of Armenia, 2014). However, to our knowledge, research data on climate change impacts on aquatic communities do not exist. If climate change concern is not acknowledged and properly addressed on the level of national development strategies and programs, the impact may be disastrous for Lake Sevan and also for the whole country.

Future prospects of Lake Sevan

A new thoroughly elaborated and integrated lake restoration strategy is essentially required to protect the biological and water resources of the lake, to support regional economic growth based on lake-related tourism and fisheries, and to ensure the preservation of its cultural values. Lake Sevan's commercial fish stock appears to be drastically declining at present. In the previous century, efforts to replenish the trout population through the release of fry/fingerlings bred in fish farms were implemented. For example, during 1946-1980 a total of 1.7-16 million fry were annually released into the lake (Gabrielyan, 2010) supplemented from 2015-2018 by another 2.3 million fingerlings (ArmInfo News Agency, https://finport.am/full_news.php?id=35757&lang=3). However, despite of this huge and continuous effort, a natural reproduction of trout was not because of poor condition of spawning rivers and inefficient poaching prevention. From 1979-1990 the coefficient of illegal fishing (official:inofficial catch) of whitefish ranged between 2.0 and 3.0, while from 1991-1998 it had increased to 2.7 to 12.7 (Gabrielyan, 2010). Thus, poaching severely exceeded legal fishery and has been a major cause for the depletion of the commercially valuable whitefish stock. Most importantly, poaching interferes with sustainable stock management because realized harvest can neither be controlled nor properly quantified reducing the precision of professional stock assessment. Illegal fishing has always existed on the lake. Nevertheless, a new strategy, if intended to be successful, should strictly address this problem.

Unfortunately, since the 1990s poaching has become one of the primary income sources for local people residing around the lake which are either fishermen or otherwise connected to fishing industry. In addition, since 1978 Lake Sevan is part of the Sevan National Park. According to this protected status, processing industries and some kinds of agricultural activities are highly limited around the lake. Thus, for efficient poaching prevention, the strategy should acknowledge this intrinsic situation and generate alternative income options for the local people to eliminate the reasons for illegal fishery. For example, creation of a new infrastructure around the lake for engaging local population in other, environmentally friendly activities may help and shall be given a proper focus. This may be achieved by attracting investors in pollution-free industries and engaging the local population into these industries. Also, a more attractive development of international tourism, using the lake as the centerpiece, would not only generate income options and welfare for the local people but would also increase the valuation of the region and public perception of Lake Sevan as a place with an excellent cultural, natural and socio-economical reputation. Such instruments may also attract investors and firms. Adequate fisheries management including long-term stock regulation ought to be an integral element of this endeavor.

The strategy should also critically assess the ways by which the available water is used. While the lake water can easily and inexpensively be used for irrigation in the Ararat Valley (main agricultural lands of Armenia), increasing water efficiency in irrigation-based agriculture should be mandatory. Pond-based aquaculture farms in the same area are another major water consumer. They currently follow a simple take-use-release strategy and refill their ponds with pumped ground water. Adequate water recycling can be a way to substantially reduce water demand and wastewater release. Treated wastewaters from aquaculture could alternatively be used for irrigation. Finally, rain water collection for domestic and industrial purposes may be considered in that area.

Given that the whole region even now suffers from a shortage in water supply and projected climate warming is likely to further worsen this situation, elaborated water management will become a main aspect of national (and transnational) politics. A plan for sustainable water use must encompass the long-term balance between water availability and demand, problems of soil salinization due to irrigation, prevention of groundwater overuse, protection of water quality by implementing state-of-the-art waste water treatment, and best management practices in agriculture. Concerning these requirements, Lake Sevan will always be at the heart of any Armenian water strategy as it contains a major share of the country's water resources.

In terms of future management needs, the stabilization of the lake's water level is of utmost importance. Although current goals still call for the water level to rise, a more realistic target may be to maintain its current level, *i.e.,* to prevent another period of falling water levels. Moreover, issues of contamination by industrial and domestic waste must be addressed immediately and measures for their reduction must be enacted.

To improve and protect the lake's ecosystem and increase its resilience in the face of climate change, nutrient inputs from the catchment, and trout aquaculture, only an integrated approach that includes both water quantity and water quality will be effective. This necessitates a sophisticated scientific basis that provides trustworthy assessments of current and future water availability as well as guidelines for water quality management. In this regard, an integrated strategy for restoration and protection will play a crucial role. Moreover, it has to address all aspects of economic growth connected to the lake's resources. The conceptual work for such an integrated strategy has already begun but it will require ongoing efforts, including proper implementation control. This will hopefully safeguard this unique freshwater ecosystem, water resource, and cultural heritage for future generations.

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